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Determination of machinability considering degradation of accuracy over machine tool life cycle

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Abstract

The emergence of financially and environmentally conscious manufacturing has resulted in a need for efficient process planning in today's manufacturing system. Process planning based on nominal machine tool specifications, limits predictive capabilities with regard to the final part quality. More efficient process plans can be achieved once an accurate machine tool capability profile has been defined. Machine tool capability profiles deliver up-to-date resource attributes such as availability, health and applicability into the process-planning stage. A manufacturing resource's health degrades continuously throughout its life cycle due to environmental factors, part wear, operator competence, etc. Identifying and compensating for these factors during process planning may alleviate material wastage and machining estimate production time and cost via decision-making mechanisms. In this paper, the STEP-NC Standard is used to represent a model of machining resources, including worktable, spindle and tool status during a machine tool's operational lifespan. A prototype of machine tool capability profile enabled process planning system is then presented and tested to highlight the advantages of this approach.

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Keywords: Machining Capability Profile; Process Planning; CNC Machines

1. Introduction

Process planning for metal cutting is among the most knowledge-intensive activities due to information flow between manufacturing resources [1]. Significant effort has been put into to the automation of CAD/CAPP/CAM processes, facilitated through the application of new technologies such as feature-based technologies [2], neural networks [3], genetic algorithms [4], etc. However, there is a lack of smooth information flow between these processes since there is limited information about manufacturing resource status. Finding solution for this gap needs a reliable and accurate realisation of CNC machine specifications as well as final product requirements. Furthermore, A CNC machine may fail to work on its best ability due to thermal variations, spindle vibrations, tool wears and servo errors. Execution of process plans generated without considering manufacturing resources degradation may produce out of tolerance parts. Comparing actual machining capability against product specifications such as feature tolerance and surface roughness is an essential enabler to produce reliable process plans. Machining capability profile (MCP) has emerged as a result of the need for identifying and compensating those errors caused during machining processes.

A capability profile is defined as a representation of the capabilities that a specific machine tool will be able to provide in a specific time on a specific product [5]. Based on the information within this profile, a manufacturing decision making process can ensure the appropriateness and the quality of process plans. Recent development on STEP-NC Standards [6] supported CAPP systems by bringing the ability of process planning based on features and resources defined within the STEP-NC codes. STEP-NC has been selected due to its simplicity in handling semantic terms in machine tool modelling, and its promising potential for representing manufacturing resources. Integrating STEP-NC technologies

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with manufacturing capability profiles enables SMEs to use from their current resources efficiently whilst minimizing the time and cost of their manufactured parts. Using from all potentials of old CNC machines bring significant reduction on the waste generated during manufacturing operations.

Cyber-physical systems are integration of computation physical processes. Embedded computers and networks monitor and control the physical processes thorough several networks including the internet, usually with feedback loops where physical processes affect computation and vise versa [7]. Cyber-physical system design has been used to demonstrate the dynamics of capturing manufacturing capabilities through proposed framework.

The aim of this research is to develop a framework for capturing manufacturing capability profile to ease transformation from design to production considering product specifications. Benefits of having such a system are as follows:

- Automating CAD/CAPP/CAM/CNC chain, and shifting toward CAD/MCP-CAPP/CNC
- Efficient use of current manufacturing resources
- Reduce wastes from intolerance and defective parts

In this paper, machining capability profile design processes have been discussed, and incorporated with STEP-NC platform. An example shows the simplified function of machining capability profile has been presented at the end.

2. Current process planning challenges

Process planning in metal cutting is the consolidation of activities that seek to define necessary steps to change the shape of raw material to the desired product [8]. The activities range from the selection of technologies and manufacturability analysis at the high level to sequencing operations and generating numerical control codes at the low level. Significant research has been done to reduce the reliance of process planning on human process planners or computer-aided systems. However, process planning relies heavily on the availability of production resource information, which is neither clear for human process planners nor computer-aided systems.

2.1. Transfer of knowledge and information

Process planning is considered to be a labour-intensive, time consuming and tedious activity [1]. Human planners utilize their knowledge of technological capability of various types of machines while computer-aided systems rely on resource models. CAM systems require users to select a machine type before generating tool paths and post-processors relay on internal models of machine to achieve their purpose. Although, significant efforts have been dedicated to smoothen information flow between CAD/CAPP/CAM processes, however, there is no feasible off-the-shelf solution can yet be implemented effectively in industry. Emergence of STEP-NC Standard brings the possibility of generating process plans based on given tolerances, working steps and cutting tools. STEP-NC aims to automate the CAD/CAPP/CAM processes; However, There is no consideration of manufacturing resource capability to generate STEP-NC codes yet. Therefore, process plans generate based on STEP-NC may result in out of tolerance parts at the end.

Large companies have to be able to assess their machining capabilities across various CNC machines to ensure that their finished parts are in tolerance during machine's life. In order to compile an overview of an SMEs manufacturing capability, the only approach that is currently available is to manually assess individual machines and combine them using tools such as spreadsheets to form the overall capability profile of the company [9]. Also, large amount of information would be lost, if the acknowledged person left company. Compiling a joint capability profile with a number of companies can become exceedingly time consuming and thus dynamic formation of virtual enterprise is currently done without a full assessment of the joint capability. The manufacturing capability profile system should capture and store the technical machining capability for each CNC in a company. The system should also be able to combine the captured information from the machines to compile the overall manufacturing capability of large companies. Furthermore, machining capability profile system should be able to communicate with other systems installed in other places to combine the capability of several companies and provide this information to the companies in order to assess the capability resulting from the formation of dynamic virtual enterprises comprised of several SMEs. This information can then be used to approach clients with jobs bigger than the capability of any single SME.

2.2. Capturing capability profiles of manufacturing resources

During production, the conditions of all manufacturing resources degrade with usage and age, and process plans generated based on those resources are not feasible anymore [10]. For instance, a 3-axis milling machine may have 21 internal errors. Therefore, advance prediction methods need to be developed in order to detect manufacturing resource degradation and performance loss before process planning.

It is prerequisite for the capability profile data model, to has manufacturing resource data model that can represent CNC machining system resource individually [11]. Information required by resource models has been classified as categories, attributes and relationships for development a common representation of manufacturing resource elements [12]. LOOM [13] and OOMRM [14] languages have been utilised to capture the manufacturing capabilities, but use of them remained controversial due to difficulties in handling semantic terms in machine tool modelling. Also, neither of these reflect the actual capability of the machining resources to perform the required machining tasks without failure.

3. Capturing dynamic data from manufacturing resources

Ensuring competence and capability of a company needs to assess various machines existed in a company. Increasing complex geometry and tight tolerance limit the selection of appropriate machine tools, and only few machines are capable to meet those requirements. Fig. 1. shows the cyber-physical architecture of proposed framework for capturing machining capability profile.

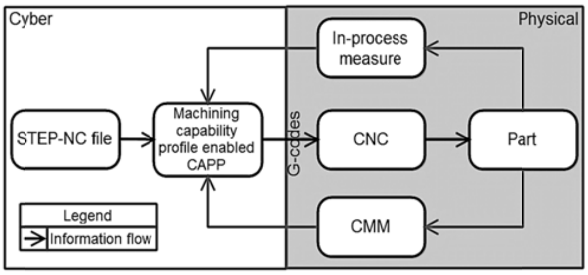

Fig. 1. Cyber-physical architecture of proposed software.

3.1. STEP-NC resource data models

Recently developed ISO 14649 series [6], which use EXPRESS language [15] to define entities in object-oriented manner has been emerged as a result of International efforts to deliver a comprehensive data model for machine tools. ISO 14649 part 201 [16] has been selected for machining capability profile development due to its promising potential for representing manufacturing resources capabilities. Machine tool specifications defined in this Standard contain all aspects of machine tool configurations and elements. To describe the specifications of machine tool, standardised data model has been developed based on ISO 14649 part 201, and tightly connected to machining capability profile data model.

The data models developed for manufacturing resources should contain sufficient information to support an accurate construction of manufacturing capability. These machine tool health parameters and their testing protocols have been covered comprehensively in ISO 230 series [17], ISO 10791 [18] and ASME B5.54 [19]. Tests designed for assessing machine tool's accuracy ensure that machining resources are on their healthy condition. However, there is no standard way to evaluate the capability of machine tools based on the above testing protocols.

3.2. Manufacturing resources constraints

Often in industry, specific constraints are imposed on manufacturing resources by external factors such as managerial decisions and new standards. For example, a specific CNC machine might be allocated to produce a specific part and not be used for other parts, without considering the fact that the machine has the capability to produce other parts. These production policies are not always considered when the process plans for a component is being generated.

Also, constraints associated with machining parameters have to be considered before generating process plans. The logical selection of appropriate tooling and machining strategies is an essential enabler when determining the most effective plan with respect to the available resources.

4. Process planning supported by capability profiles

4.1. Machining capability profile elements

Most of the information required for machining capability development could be retrieved from machining specification schema, which has been defined in ISO 14649-201, examples include machine size, tool length and controller configuration. But, other capability entities have to be developed for assessing machining feasibility of a product. The UML activity diagram of the tests required for capturing capability profile of a CNC machine has been depicted in Fig. 2.

Proposed framework for developing manufacturing capability profile contains following information:

- Tooling capability: investigate the capability of cutting tools available inside machine tool magazine. The tool life of each cutting tools has to be stored in tooling capability utilising sensors or cutting tool estimation algorithms [20].
- Working area capability: evaluate the degree of freedom to move along worktables and axes. The sizes of workpiece and worktable have to be considered before generating STEP-NC code.
- Axes accuracy: check the accuracy and repeatability of X, Y and Z axes. Testing protocols covered in ISO 230 series have to be done on regular basis so as to have the most updated status of axes accuracy. The EXPRESS-G diagram for axes accuracy has been shown in Fig. 3.
- Feed drive capability: assess the feed drive capability to perform required tasks. An example includes minimum and maximum feed rates, which can be delivered by feed drive.
- Spindle drive capability: captures the spindle capability to machine within the required tolerances. An example includes the range of cutting speed may be delivered by a spindle unit.
- Overall capability: capabilities that change with machine types and models evaluated based on specific capability profiles, such as NC controller, machine class and machine size.

Manufacturing capability profiles have to be updated on a regular basis so as to represent the most recent machine tool health status. Manufacturing capability data points store health data for machine tool elements such as worktable, spindle and tool indicating their individual performance. For instance, tooling capability not only shows the availability of the tool required for machining features but also stores tool wear and tool life information inside machining capability data points. EXPRESS-G diagram for machining capability data point has been depicted in Fig. 4.

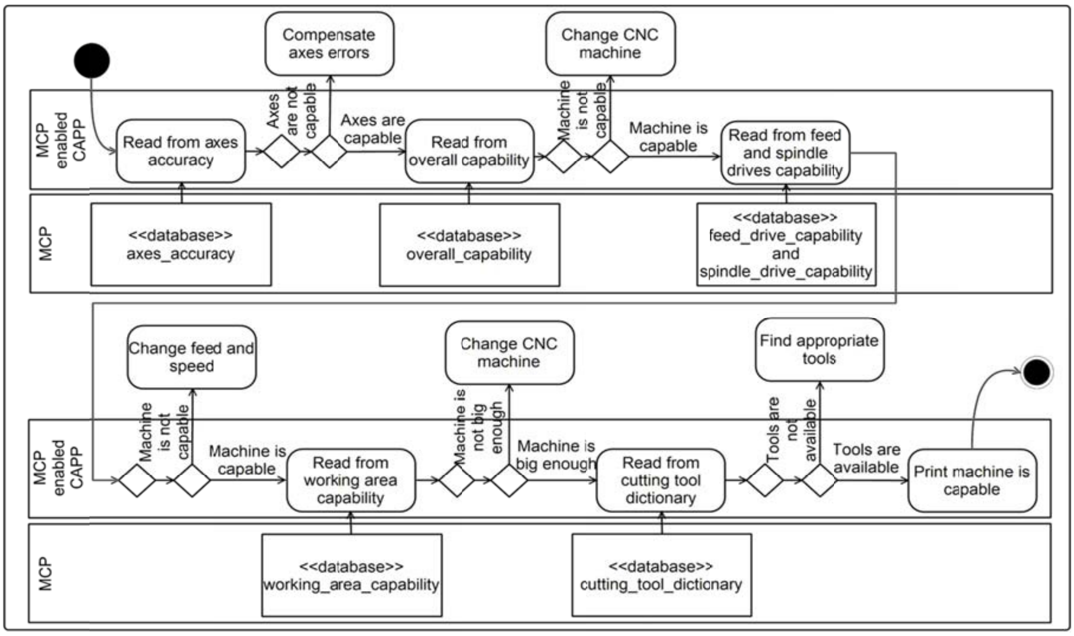

Fig. 2. UML activity diagram of manufacturing capability tests.

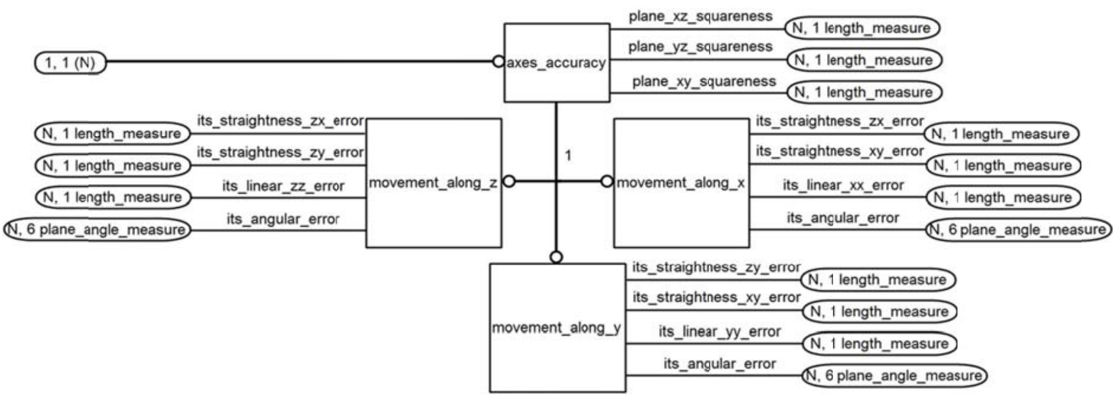

Fig. 3. The EXPRESS-G diagram of axes_accuracy.

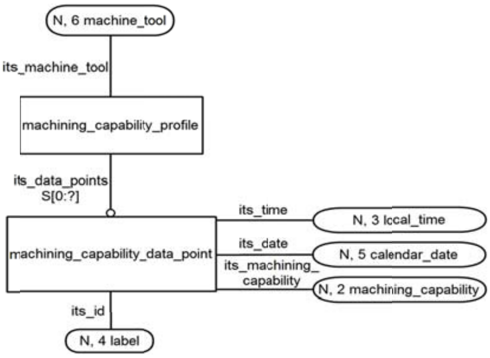

Fig 4. The EXPRESS-G diagram of machining_capability_data_point.

Developing accurate and comprehensive cutting tool dictionary, which shows the number of available and healthy tools inside the machine tool's magazine, is essential for evaluating machine tool capability. Process plans generated without considering tool age are not be able to deliver required quality during production. Tool change prediction model has been mathematically formulated [20], and online tool wear monitoring system has been fulfilled by the application of sensors in machine tools. Related International Standard, ISO 14649-111 [21] has been used for the computer interpretable representation of milling cutting tool data. ISO 14649-111 has been integrated with developed cutting tool dictionary for defining milling tool specifications. The EXPRESS-G representation of data model developed for cutting tool dictionary has been graphed in Fig. 5.

5. Manufacturing capability profiles development

5.1. Requirements excerpted from STEP-NC

Emerging STEP-NC technologies enable to define manufacturing features and their associated machining strategies, cutting tools and tolerances in a computer interpretable format. Data required to assess manufacturing capability has to be parsed from STEP-NC file, while ensuring that machining resources are on their healthy status to deliver those requirements. Fig. 6. highlights information excerpted from a rectangular shape defined in ISO 14649-11.

If the NC controller has the ability to generate toolpaths or to make decision about the tool used, it is the controller responsibility to meet these tolerance requirements. On the other hand, data provided to the NC controller for explicit specification of movements will have no tolerances as the controller cannot do more that try to follow the given theoretical values to the best of its abilities.

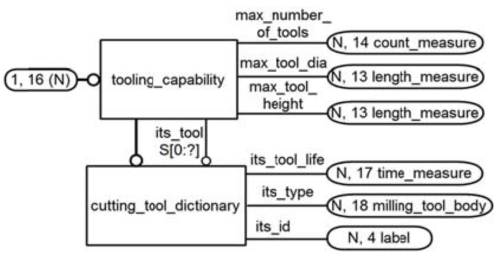

Fig. 5. The EXPRESS-G diagram of cutting_tool_dictionary.

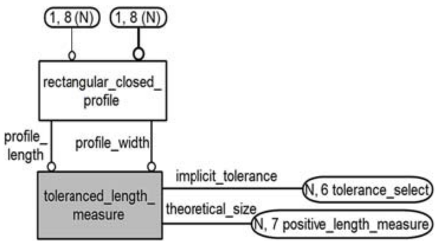

Fig. 6. The EXPRESS-G diagram of tolerance_length_measure.

Similarly, cutting tools that are appropriate for machining specific features are recommended by the STEP-NC code; in accordance with ISO 14649-111. However, there is no consideration of the availability and health of those required cutting tools. Thus, manufacturing capability profile interpreter developed for ensuring that a machine tool can deliver the requested tasks based on its actual ability.

5.2. Validation of the prototype

The proposed framework has been tested with a 3-axis milling machine for machining a pocket. Fig. 7. shows the STEP-NC codes generated for machining a rectangular closed pocket with its assigned tolerances and milling tools.

```
#1= PROJECT('EXECUTE EXAMPLE1',#2,(#3),$,$,$);
#2= WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14),$,#6,$);
#3= WORKPIECE('SIMPLE WORKPIECE',#4,0.010,$,$,$,(#66,#67,#68,#69));
#4= MATERIAL('ST-50','STEEL',(#5));
#5= PROPERTY_PARAMETER('E=200000N/M2');
#6= SETUP('SETUP1',#71,#62,(#7));
#7= WORKPIECE_SETUP(#3,#74,$,$,());
..
#13=MACHINING_WORKINGSTEP('WS ROUGH POCKET1',#62,#18,#22,$);
..
#18= CLOSED_POCKET('POCKET1',#4,(#22,#23),#84,#65,(),$,#27,#35,#37,#28);
..
#22=BOTTOM_AND_SIDE_ROUGH_MILLING($,$,'ROUGH
POCKET1',15.000,$,#39,#50,#41,$,$,$,#51,2.500,5.000,1.000,0.500);
..
#35=TOLERANCED_LENGTH_MEASURE(80.000,#36);
#36=PLUS_MINUS_VALUE(0.100,0.100,3);
#37=TOLERANCED_LENGTH_MEASURE(50.000,#38);
#38=PLUS_MINUS_VALUE(0.100,0.100,3);
..
#39=MILLING_CUTTING_TOOL('MILL 20MM',#29,(#125),80.000,$,$);
```

Fig. 7. A sample STEP-NC code for machining a closed pocket.

Capability analysis of a 3-axis Bridgeport machine has been done based on the testing protocols retrieved from machine's handbook and ISO 230 series. A sample capability profile has been generated for a Bridgeport machine in order to assess the required tolerances shown in Fig. 7. based on actual Bridgeport machine abilities. Fig. 8. listed the capability attributes dedicated to the Bridgeport milling machine.

The values stored in Bridgeport capability profile show that the machine axes have enough accuracy to machine a rectangular closed pocket. Also, cutting tool required for this task is available inside the Bridgeport magazine. The extended version of capability profile interpreter contains more machine health parameters such as feed drive capability, spindle drive capability and working area capability. The same machining procedure has been taken to drill a hole as its shown in Fig. 9.

According to machining capability profile presented in Fig. 8., the Bridgeport machine is not capable of drilling the hole within the defined tolerances. The reasons for those incompatibilities within the STEP-NC codes have been highlighted. The machine axes are not sufficiently accurate to adhere to the desired geometrical tolerances. Additionally, there are no appropriate drilling tools to finish this feature. Working area of Bridgeport machine is not big enough to handle machining operations either.

```
DATA;
#1=MACHINING_CAPABILITY_PROFILE(#22,(#2));
#2=MACHINING_CAPABILITY_DATA_POINT('Bridgeport VMC 610 XP2 capability
test',$,#3,#4);
#3=CALENDAR_DATE(2013,31,7);
#4=LOCAL_TIME(16,0,0.0,$);
#5=FEED_DRIVE_CAPABILITY($,0.1,0.0,$,$);
#6=SPINDLE_DRIVE_CAPABILITY($,$,3000.0,0.0);
#7=TOOLING_CAPABILITY(13.0,66.0,20.0,(#13,#16,#19));
#8=WORKING_AREA_CAPABILITY(40.0,40.0,40.0,$,$,$);
#9=OVERALL_CAPABILITY(.MILLING_MACHINE.,.SIEMENS.,6000.0,3500.0,1500.0)
;
#10=MOVEMENT_ALONG_X(0.05,0.05,0.05,0.05, 5.0E-5,0.05,0.05);
#11=MOVEMENT_ALONG_Y(0.05,0.05,0.05,0.05, 5.0E-5,0.05,0.05);
#12=MOVEMENT_ALONG_Z(0.05,0.05,0.05,0.05, 5.0E-5,0.05,0.05);
#13=CUTTING_TOOL_DICTIONARY($,$,$,(),'rough mill',#14,150.0);
#14=MILLING_TOOL_BODY(#15,2,$,$,$);
#15=MILLING_TOOL_DIMENSION(66.0,$,$,$,$,$,$);
#16=CUTTING_TOOL_DICTIONARY($,$,$,(),'end mill',#17,170.0);
#17=MILLING_TOOL_BODY(#18,2,$,$,$);
#18=MILLING_TOOL_DIMENSION(66.0,$,$,$,$,$,$);
#19=CUTTING_TOOL_DICTIONARY($,$,$,(),'end mill',#20,180.0);
#20=MILLING_TOOL_BODY(#21,2,$,$,$);
#21=MILLING_TOOL_DIMENSION(20.0,$,$,$,$,$,$);
#22=MACHINE_TOOL_SPECIFICATION('Bridgeport VMC 610
XP2',.MILLING_MACHINE.,#23,(#24),$,$,$,#25,$,(#26,#27,#28));
#23=DEVICE_ID('Bridgeport','VMC 610 XP2','723703','Hardinge Group',$);
#24=MACHINING_CAPABILITY();
#25=NC_CONTROLLER('SINUMERIK','Siemens',.INCH_AND_METRIC.,5.0,4.0,1.0
,0.0010,0.01,2.0,(),(.LINEAR.),$,$,$,$,(),(),(),$,$);
#26=MACHINE_TOOL_ELEMENT('X AXIS',$,$,());
#27=MACHINE_TOOL_ELEMENT('Y AXIS',$,$,());
#28=MACHINE_TOOL_ELEMENT('Z AXIS',$,$,());
ENDSEC;
END-ISO-10303-21
```

Fig. 8. A sample machining capability profile generated for Bridgeport milling machine.

```
#1= PROJECT('EXECUTE EXAMPLE1',#2,(#3),$,$,$);
#2= WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14),$,#6,$);
#3= WORKPIECE('SIMPLE WORKPIECE',#4,0.010,$,$,$,(#66,#67,#68,#69));
#4= MATERIAL('ST-50','STEEL',(#5));
#5= PROPERTY_PARAMETER('E=200000N/M2');
#6= SETUP('SETUP1',#71,#62,(#7));
#7= WORKPIECE_SETUP(#3,#74,$,$,());
..
#11= MACHINING_WORKINGSTEP('WS DRILL HOLE1',#62,#17,#20,$);
..
#17= ROUND_HOLE('HOLE1 D=22MM',#4,(#20,#21),#81,#64,#56,$,#26);
..
#20= DRILLING($,$,'DRILL HOLE1',10.000,$,#44,#45,#41,$,$,$,$,$,#46);
..
#56= TOLERANCED_LENGTH_MEASURE(22.000,#57);
#57= PLUS_MINUS_VALUE(0.0100,0.0100,3);
..
#44= MILLING_CUTTING_TOOL('SPIRAL_DRILL_20MM',#31,(#126),90.000,$,$);
..
#66= CARTESIAN_POINT('CLAMPING_POSITION1',(0.000,40.000,50.000));
#67= CARTESIAN_POINT('CLAMPING_POSITION2',(100.000,40.000,50.000));
#68= CARTESIAN_POINT('CLAMPING_POSITION3',(0.000,200.000,50.000));
#69= CARTESIAN_POINT('CLAMPING_POSITION4',(100.000,200.000,50.000));
```

Fig. 9. A sample STEP-NC code for drilling a hole.

6. Conclusion and future work

This paper has launched a new approach for CAPP system to develop manufacturing capability profiles dealing with obsolete CNC machines and process performances. Degradation of manufacturing resources can cause out of tolerance parts being generated over the resource's operational life span. Identifying and compensating factors influenced by machining resources degradation may reduce waste and time of production. Proposed framework for capturing the capability of machine tool has been integrated with machine tool specification model introduced in ISO 14649-201. Testing protocols of machine health has been excerpted from ISO 230 series and compared against the machining requirements defined in ISO 14649. The validation of proposed framework has been explored with a case on 3 axis milling machine. As a further development, the MCP outlined in this paper may be integrated within a machining capability interpreter for further exploitation of the approach.

Acknowledgements

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References

[1] Halevi, G., Weill, R., 1995. Principles of process planning a logical approach, Chapman & Hall, London.
[2] Anderson, D.C., Chang, T.C., 1990. Geometric reasoning in feature-based design and process planning, Computers and Graphics 14, p. 225.
[3] Prahbhakar, S., Henderson, M.R., 2000. Automatic form-feature recognition using neural-network-based techniques on boundary representation of solid models, Computer_Aided Design 24, p. 381.
[4] Awadh, B., Sepehri, N., Hawaleshka, O., 1995. A computer-aided process planning model based on genetic algorithms, Computers and Operations Research 22, p. 841.
[5] Newman, S.T., Nassehi, A., 2009. Machine tool capability profile for intelligent process planning, CIRP Annals - Manufacturing Technology 58, p. 421.
[6] ISO 14649-1, 2003. Industrial automation systems and integration, Data model for computerized numerical controllers, Part 1: overview and fundamental principles.
[7] Lee, E.A., 2008. Cyber physical systems: design challenges, 11th IEEE Syposium on Object Oriented Real Time Distributed Computing, p. 363.
[8] ElMaraghy, H., 1993. Evolution and future perspectives of CAPP, Annals of the CIRP 42, p. 739.
[9] Helander precision engineering ltd., 2013. availble from: http://www.helander.co.uk/LiteratureRetrieve.aspx?ID=96734.
[10] Ramesh, R., Mannan, M.A., Poo, A.N., 2000. Error compensation in machine tools - a review: part 1: geometric, cutting-force induces and fixture-dependent errors, International Journal of Machine tools and Manufacture 40, p. 1235.
[11] Nassehi, A., Parag, V., 2009. A STEP-NC compliant methodology for modelling manufacturing resources, Advanced Design and Manufacturing Based on STEP, p. 261.
[12] Jurrens, K., Fowler, J., Algeo, E., 1995. Modelling of manufacturing resource information, National Institute of Standards and Technology.
[13] Wilczynski, D., Lipkis, T., 1993, Machine modelling in LOOM, available from: http://www.isi.edu/isd/LOOM/papers/LOOM-PAPERS.html.
[14] Zhang, Y., Feng, S., 1999. Object oriented manufacturing resource modelling for adaptive process planning, International Journal of Production Research 37, p. 4179.
[15] ISO 10303-11, 2004. Industrial automation systems and integration, Product data representation and exchange, Part 11: Description methods: The EXPRESS language reference manual.
[16] ISO 14649-201, 2011. Industrial automation systems and integration - Physical device control, Data model for computerized numerical controllers, Part 201: Machine tool data for cutting processes.
[17] ISO 230-1, 2012. Test codes for machine tools, Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions.
[18] ISO 10791-1, 1998. Test conditions for machining centres, Part 1: Geomteric tests for machines with horizontal spindle and with accessory heads (horizontal Z-axis).
[19] ASME B5.54, 2005. Methods for performance evaluation of computer numerically controlled machining centres.
[20] Kramer, B.M., 1986. A comprehensive tool wear model, Annals of the CIRP 35, p. 67.
[21] ISO 14649-111, 2010. Industrial automation systems and integration - data model for computerized numerical controllers - Part 111: tools for milling machines.